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Characterization of Hydrocarbon-bearing Fluid Inclusion in Sandstones of Jaisalmer Basin, Rajasthan: A Preliminary Approach

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Abstract: The quartz grains from the sandstone of Jaisalmer, Pariwar and Goru Formations of the Jaisalmer basin, Rajasthan, India, exhibits a variety of primary and secondary fluid inclusions. Most of them are hydrocarbon bearing fluid inclusions. Laser Raman studies indicate that the primary fluid inclusions were mostly having aliphatic hydrocarbons with lower degree of maturity, while the secondary fluid inclusions were generally with aliphatic as well as aromatic hydrocarbons with higher degree of maturity. This inference was consistent with their fluorescence characteristics. The homogenization temperatures of primary monophase CH_4 rich fluid inclusions varied from -80°C to -100°C, whereas the primary biphase fluid inclusions (CH_4-CO_2) homogenized between +80°C and +150°C. The secondary petroleum rich monophase fluid inclusions were having homogenization temperature between -80°C to -90°C, whereas the secondary biphase fluid inclusions homogenized between +130°C and +180°C. Most of the secondary biphase fluid inclusions were having the mixtures of H_2O-CO_2-NaCl, and were identified on the basis clathrate formation and they got homogenized between +140°C and + 250 °C. The three past events of migration of petroleum inferred in the host rock which were marked by the presence of characteristic secondary fluid inclusions. They were identified on the basis of cross-cutting relationships of different trails of fluid inclusions in the quartz. The cement generation in the basin might have been occurred in two stages as per the fluid inclusion petrography.

Keywords: Hydrocarbon bearing fluid inclusions, Fluorescence microscopy, Laser Raman, Micro-geothermometry, Jaisalmer basin, Rajasthan.

INTRODUCTION

The fluid inclusions in petroliferous rocks have been used to determine the physical limit of petroleum migration and to reconstruct the geo-thermal history of the sedimentary basin (Burruss, 1981; Pagel, et al. 1986 and McLimans, 1987). Micro-thermometry is the most important tool which could classify the fluid inclusions, but the interpretation of hydrocarbon bearing fluid inclusion data this way is problematic. Therefore, researchers in the past have approached, chemical analysis of hydrocarbons entrapped in fluid inclusions (Horsfield and McLimans, 1984; Jochum et al. 1995 a,b). The results of fluid inclusion research were relevant to our understanding of many natural sub-surface processes in which fluids play a role, such as petroleum transport, generation, migration in diagenetic environment (Munz, 2001).

Fluid inclusions in sedimentary rocks of a particular basin can provide valuable information with respect to the geological evolution of the basin. Trapping of fluid inclusions in the host minerals may occur at different stages of basin development, but were most common in the deeper parts of the earth's crust. Mostly aqueous fluids were dominating in sedimentary systems, and were actively participating in diagenetic processes (Goldstein, 2001).

This paper aims at the characterization of hydrocarbon bearing fluid inclusions in quartz grain in the bore hole sample of host of sandstones and their evolution/ migration in the sedimentary rocks of Jaisalmer basin, Rajasthan, India.

GEOLOGY OF JAISALMER BASIN

The Stratigraphy and the evolution of the Jaisalmer basin has been well documented by pioneer researchers (Sinha et al. 1998). The development of structural trends, rift basins

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and different kinds of igneous intrusions over the west coast of India and adjoining regions from the Jurassic age were affected by three major tectonic events; 1) the breaking away of Africa from the plate consisting of India, Madagascar and Seychelles during the middle to late Jurassic period; 2) the breakup of Madagascar from the west coast of India during middle to late Cretaceous period, probably under the influence of the Marion Plume (Storey et al. 1995; Raval and Veeraswamy, 2003); 3) Breakup of Seychelles Plateau from the Indian plate, followed by the eruption of the Deccan Trap lavas due to interaction between the Reunion Plume and the overriding lithospheric plate, during late Cretaceous (Duncan and Pyle, 1988).

Three major orogenic trends namely the NNW–SSE Dharwar in the southern part, the NE–SW trending Aravalli in the northeastern part and ENE–WSW Satpura in the central part converges in western India (Biswas, 1987). The second episode of basin evolution with a prominent hiatus starting in western Rajasthan with the deposition of the typical Lathi Formation of Jurassic age. The first marine transgression occurred at the late phase of the Lathi Formation in the Jaisalmer basin during Late Bathonian – Callovian, about 165 Ma ago with the dismemberment of the Gondwanaland. There were periods of rhythmic marine transgression and regression in the Jaisalmer basin. Deposition continued at least up to the lower part of the upper Cretaceous (Roy and Jakhar, 2002). Stratigraphic record from the Jaisalmer basin indicates reopening of this Mesozoic basin during the Late Cretaceous. Two other basins, which opened almost simultaneously with this phase, are the Barmer basin and the Bikaner Nagaur basin.

With regard to the Jaisalmer basin, in the Cretaceous period, there were several phases of marine transgression and regression, which must have caused the deposition of marine and deltaic sediments in the rift system. Rapid subsidence from Late Cretaceous to Early Eocene allowed the Jaisalmer basin as well as the adjacent basins such as *Barmer,* and *Bikaner-Nagaur basins* (Fig. 1) to fill with great thicknesses of inter-bedded fluvial sands and organic rich marine shales (Sisodia and Singh, 2000). This shale might have served as local source rocks for oil, which got accumulated in the porous sandstone. The main reservoir rocks in Jaisalmer basin are the sandstones of the Goru and Pariwar Formation of lower Cretaceous age.

Sedimentation in the region was probably initiated during the Permo- Carboniferous period. During Late to Middle Jurassic, the sedimentation continued under fluvial and stable deltaic environment. There are, however, indications of deposition in shallow shelf area at least during the Permian and the Triassic. Typical Jurassic rift basins opened later probably during the Callovian age, over the basement rocks which included the Lathi Formation. The general stratigraphy as suggested by Awasthi, (2002) for the basin is given in Table 1.

Table 1. General startigraphy of the Jaisalmer basin (Awasthi, 2002)

Formation	Lithology	Thickness (m)	Age/Time
Wind blown Sand/Alluvium	Loose sand and alluvial materials	Highly variable	Recent
Shumar	Dune sands, gravels With ferruginous noduls	730	Recent to Pleistocene
Bandah	Foraminiferal limestone Clayey at the base	200	Middle Eocene
Khuiala	Shales with limestone beds and Calcareous silts.	400	Lower Eocene
Sanu	Friable sandstone with minor clays	670	Paleocene
Parh	Marls and arenaceous limestone	350	Upper Cretaceous
Goru	Sandstone and shale	565	Upper Cretaceous
Habur	Arenaceous limestones and calcareous sandstones	200	Lower Cretaceous
Pariwar	Sandstone, shale, lignite	670	Lower Cretaceous
Baisakhi/ Bhadesar	Sandstone and shale	730	Upper Jurassic
Jaisalmer	Sandstone and limestone	1130	Middle Jurassic
Lathi	Sandstone, shale and lignite	600	Lower Jurassic

(*Remark: the bold formations were considered is the present study)

STUDY AREA AND SAMPLING

The area of present investigation is situated in the Jaisalmer district of Rajasthan state, India (Fig. 1). It is limited within latitudes 26°45' N to 27°10' N and longitudes 70°45' E to 71°10' E (Survey of India Topographic maps 40 I/16, J/13). The Jaisalmer basin comprises an area of ~ 50,000 sq km. It mainly represents the westerly dipping, eastern flank of the Indus shelf (Sinha et al. 1993). The Jaisalmer basin is located in western Rajasthan and is further extended into the Pakistan. The basin is almost covered by the Thar Desert.

The core samples and data were collected from the petroleum wells, DND-1, TOT-8 and DND-2 located in the villages such as Tannot, Dandewala, Sam and Ramgarh near

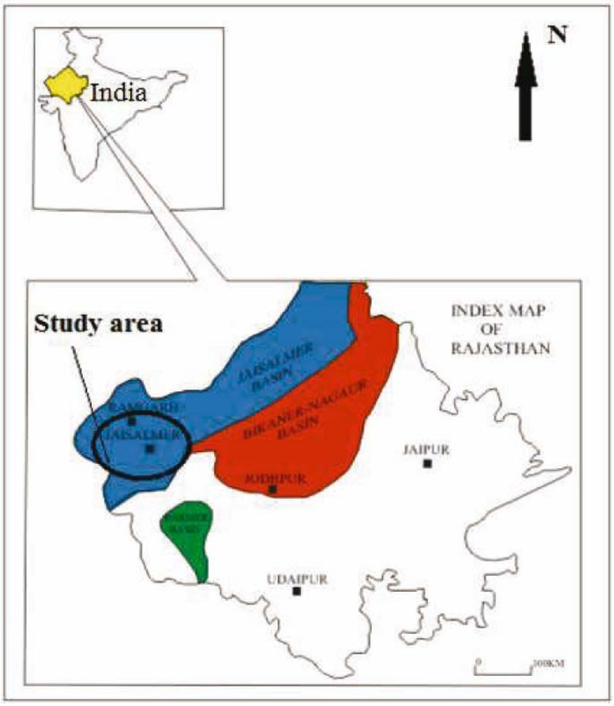

Fig.1 Map illustrating the distribution of different Neoproterozoic basins of Western Rajasthan, India (modified after Awasthi, 2002).

Jaisalmer. The petroleum wells were drilled vertically by Oil India limited (OIL), Jodhpur. The well number, sample location and formation name is given in Table 2.

Table 2. Details of samples selected for the present study (Data project, OIL, Jodhpur)

S No.	Well No.	Stratigraphic/ Formation Name	Depth of core within range (m)	Sample location
1	DND-1	Upper Guru and Jaisalmer	1240 -1245 3050-3055	N 27°44'31" E 70°08'15"
2	DND-21	Lower Guru	1921-1925	N 27°46'31" E 70°08'58"
3	TOT-8	Pariwar	2029-2038	N 27°50'56" E 70°12'20"

FLUID INCLUSIONS PETROGRAPHY

In order to study fluid inclusions, the doubly polished wafer, thick (0.3mm) and thin sections (0.03mm) were prepared with the special method outlined by Shepherd et al (1985).

A proper interpretation of fluid inclusions could be made only when textural relationships between fluid inclusions and the host mineral are understood. The primary fluid inclusions as well as secondary fluid inclusions were found in the tiny quartz grains of sandstones. Primary fluid inclusions were best identified by their relationship to growth zonation of a host mineral or crystal. Growth zonation was identified through the, (i) fluorescence (ii) cathodoluminescence and (iii) variations in the distribution pattern of different fluid inclusions trails (Fig.2). Based on the number of the phases present within a fluid inclusion at room temperature (~25 to 28°C) and the nature of origin of fluid inclusions, they can be sub categorized into different types. These fluid inclusions appear to have been developed during lithification or diagenesis. Observed fluid inclusions were mostly found containing hydrocarbon (liquid/ gas) and aqueous fluids (H_2O). Aqueous fluids mostly dominate in sedimentary systems, and must have been actively participating in diagenetic processes (Munz, 2001; Goldstein, 2001).

The hydrocarbon bearing fluid inclusions appeared yellowish to brownish colour in transmitted light (Fig.3a); whereas CO_2 bearing fluid inclusions have darkish (high

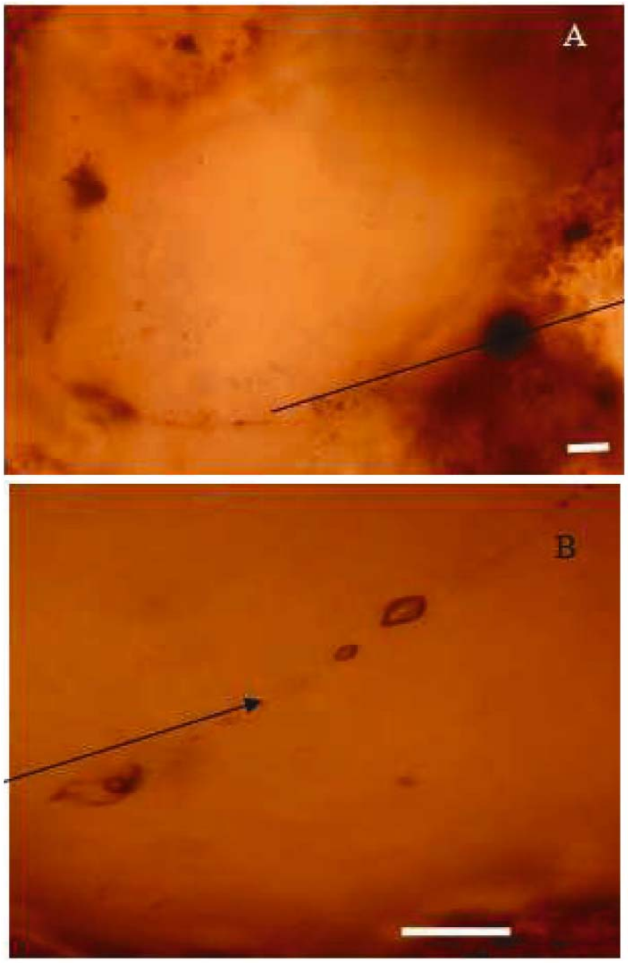

Fig.2. Photomicrographs showing the overgrowth planes of quartz, marked by the trail of fluid inclusions. (**A**) Overgrowth of quartz grain in sandstone. (**B**) Closers view of a portion of 'A' to highlight the over growth by fluid inclusions (Scale bar 10 μm).

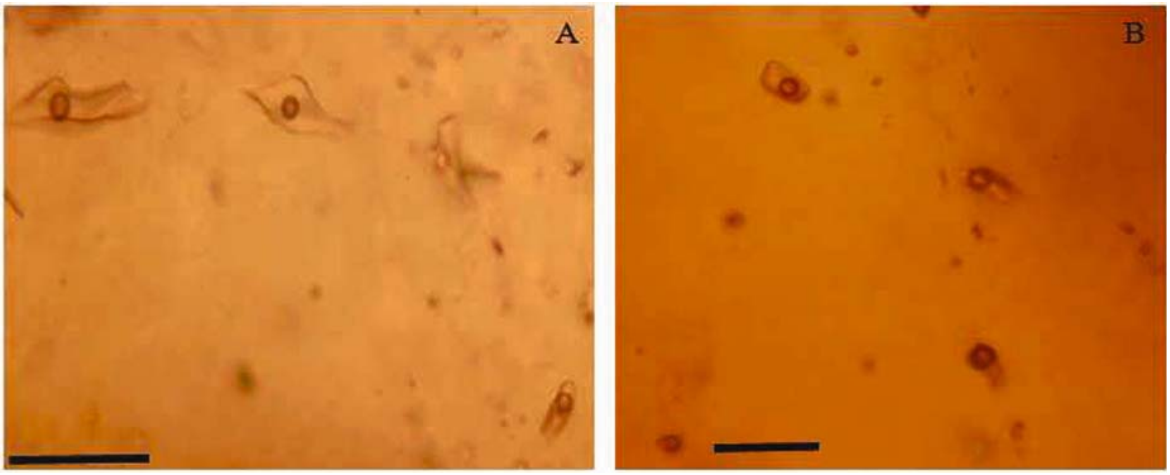

Fig.3. (A) Hydrocarbon rich biphase fluid inclusion. **(B)** Carbonic biphase inclusion. (Scale bar 10 μm),

relief) and aqueous (H_2O) are little faint (low relief), sometimes with small gas bubbles inside the inclusions (Fig.3b). The primary fluid inclusions were present in the form of monophase as well as biphase. Shapes and sizes of these monophase fluid inclusions were varied from rounded, sub-rounded to circular and within the size range of 01 to 25 μm. The shapes of the biphase fluid inclusions are varied i.e. oval, elongated, rounded, equant to negative crystal cavity and within the size range of 01 to 25 μm. Majority of both the monophase and biphase fluid inclusions were up to 15 μm in size. (Fig. 4a).

The secondary fluid inclusions found in the host quartz grains of sandstone must have been formed after the complete crystal growth of particular grain and fluid generally must have been trapped along the microscopic rehealed cracks (Fig. 5a and b). Depending upon the paleo-temperature and paleo-pressures in sandstone host rock, the secondary fluid inclusions must have been trapped in rehealed cracks with different liquid, gas/vapor ratios. A few of the hydrocarbon bearing fluid inclusion might have been trapped during homogeneous conditions, while other fluid inclusions appeared to be trapped under heterogeneous conditions. Some of the quartz grain showed cross- cutting relationship with each other, which was identified on the basis of their continuity and intersection with other trails. Fluid inclusions trapped by rehealing of micro fractures typically occurred in planar arrays or along curved arrays that cut across the growth zonation of the primary host quartz. The monophase and biphase fluid inclusion range in size from 1 to 25 μm. Majority of fluid inclusion were up to 10 μm in size (Fig.4b). In most of the biphase fluid inclusions gas bubble showed pseudo-brownian motion (Sang, 1873) and most of them appeared as yellowish brown in colour. The frequency of biphase fluid inclusions was more as compared to that of the monophase fluid inclusions (Fig. 4b) in the same grain of host minerals. A few of the

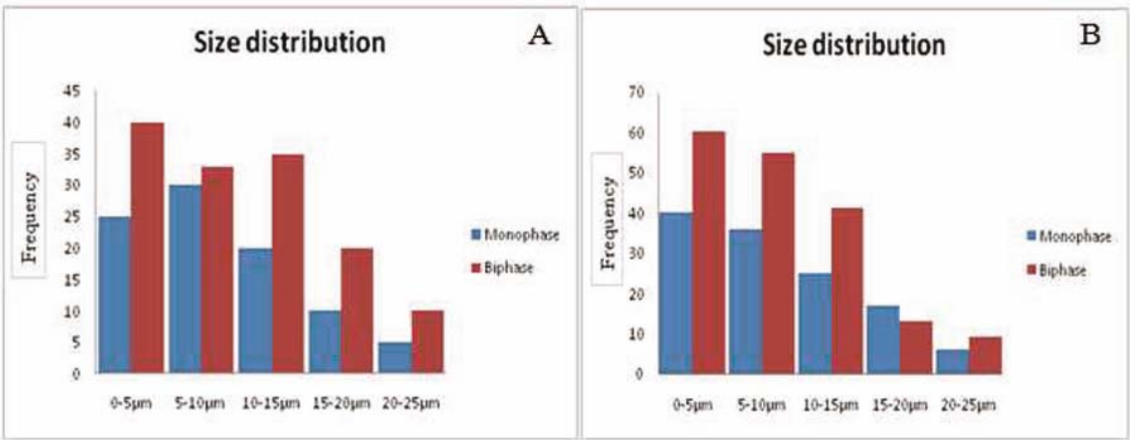

Fig.4. Histograms showing the size disribution of fluid inclusions in the sandstone. (**A**) Size distribution of primary fluid inclusions (monophase and biphase), (**B**) Size distribution of secondry fluid inclusions (monophase and biphase).

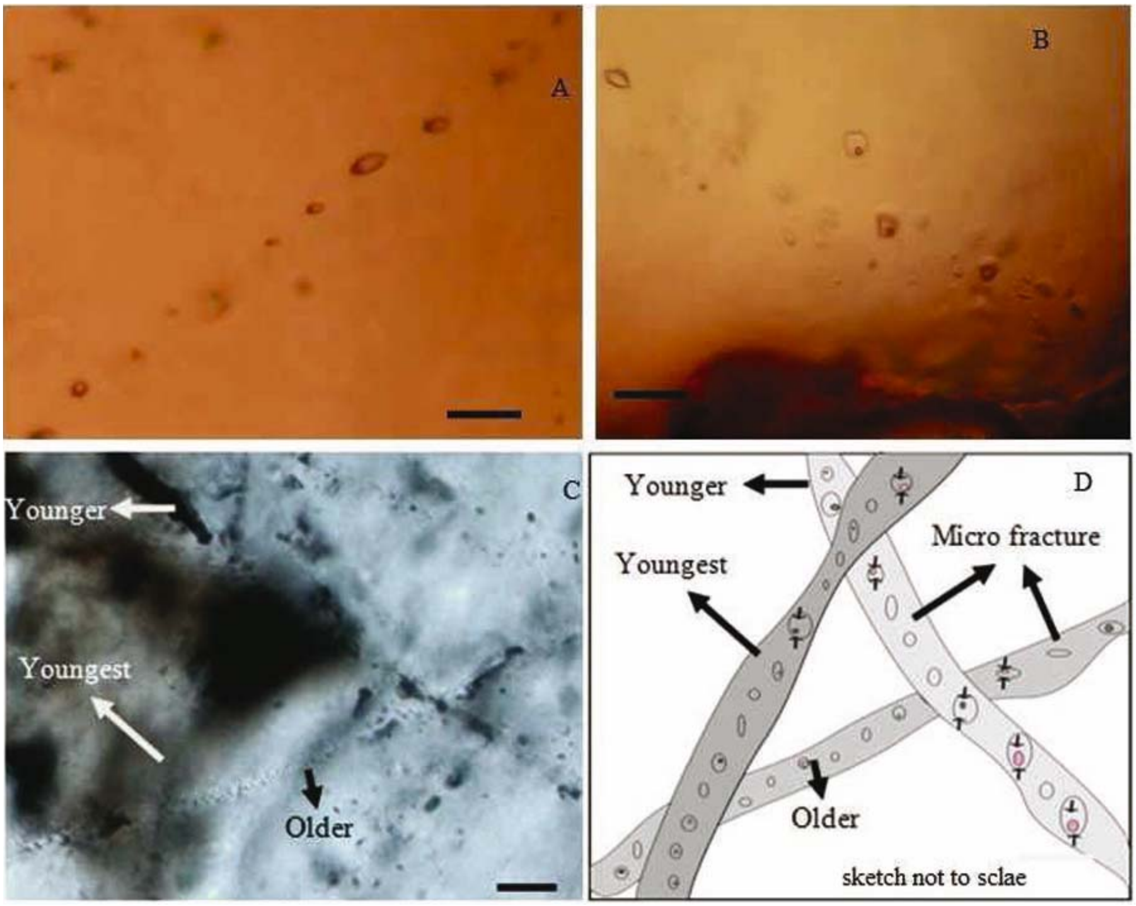

Fig.5. Photomicrograph showing inclusions trails, (**A and B**) Hydrocarbon rich, secondary monophase and biphase fluid inclusions. (**C**) Cross-crossing trails of hydrocarbon bearing fluid inclusions in sandstone (**D**) Sketch of Photomicrograph of 'C' to explain the micro-displacement and growth plane of various trails of secondary fluid inclusions and their relative age. (Scale bar 10 μm),

secondary fluid inclusion were showing cross cutting relation to each other's trail and also indicate that there were possibly three events of petroleum migration during the Middle Jurassic and Upper Cretaceous in the Jaisalmer basin (Fig. 5c and d).

A few of the fluid inclusions appeared to be of most recent origin. They might indicate the later stage of the basin evolution and identified on the basis of cross cutting relationship of the different trails of fluid inclusions and the type of cementing material present in the host rock. Some of these fluid inclusions trails were trapped after the cementation (Fig. 6a and b) and few of the fluid inclusion trails were trapped before cementation process of the host rock. Some of these probably indicate the micro tectonic effect on quartz grains of sandstone host rock of the basin (Fig. 6c and d).

MICRO THERMOMETRY

In the fluid inclusion studies, Micro-thermometric (MT) analysis is unquestionably the most popular and widely used non-destructive analytical technique (Shepherd et al. 1985). Based on the simple principle and required equipment attached to a normal optical microscope, it can be applied to a wide range of transparent minerals of geological interest. The MT studies were carried out on the Linkam THMS-600 heating, freezing stage fitted on a Leitz microscope of the fluid inclusion laboratory of the Dept. of Earth Science, IIT Bombay. The main purpose of the study was to observe and record the different phase transitions, within the primary as well secondary hydrocarbon bearing fluid inclusions in quartz grains from different sandstone host rocks.

Most of the primary monophase fluid inclusions were dominated by CH_4 (gas/liquid) at room temperature (~ 25 to 28°C). The presence of methane was inferred based on its characteristic appearance. A few of the primary monophase fluid inclusions rich in aqueous phase (H_2O) were also observed and studied during cooling of gas rich monophase fluid inclusions. Around,-82°C, heterogenization was observed in the said fluid inclusion rich in CH_4. During

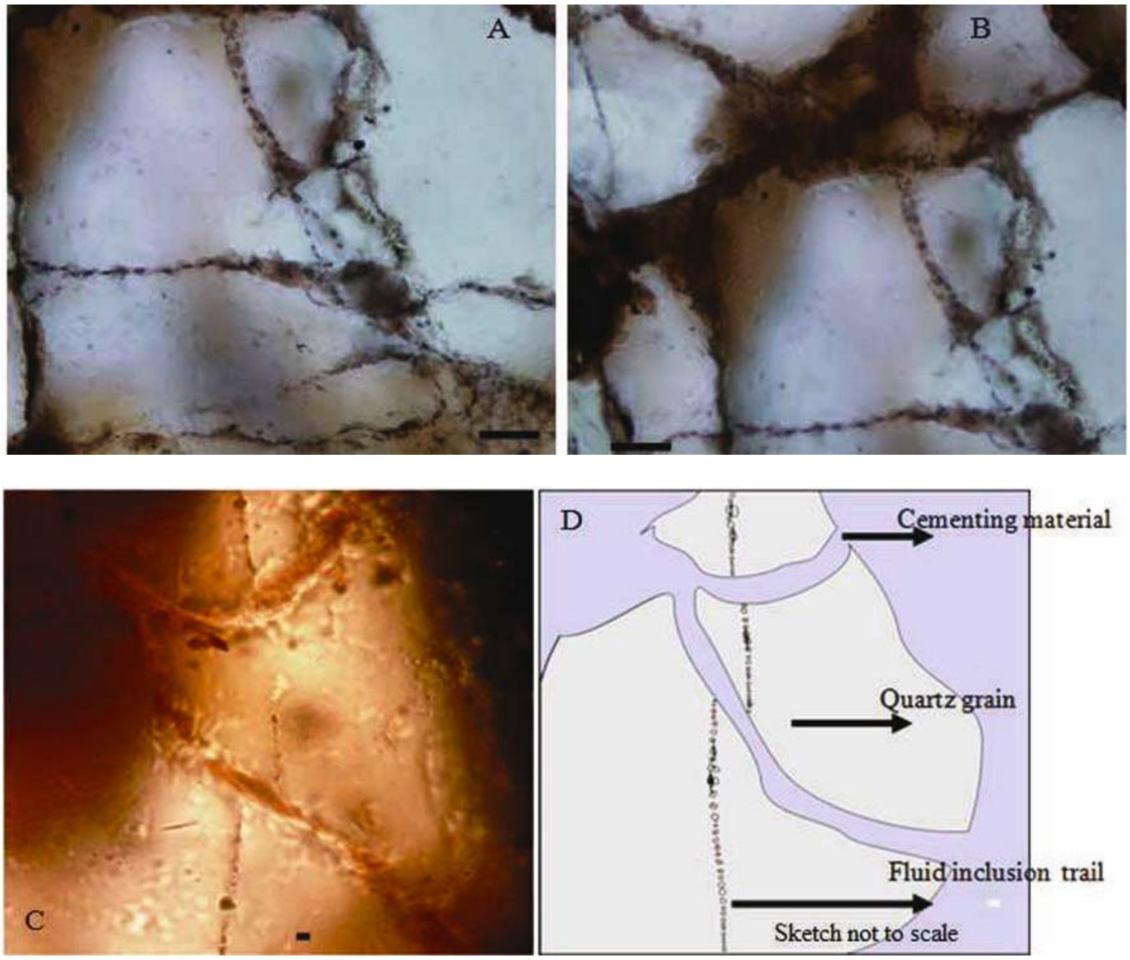

Fig.6. Photomicrograph illustrating the relation between cementation and emplacement of fluid inclusions, (**A** and **B**) Hydrocarbon rich, secondary monophase and biphase fluid inclusions formed after the cementation. (**C** and **D**) Trail of secondary hydrocarbon bearing fluid inclusions off-set by later cementation of the sandstone host rock. (Scale bar 10 µm)

further cooling with the help of liquid nitrogen, more liquid got separated from gas and around, -182°C, liquid, solid and vapour of CH_4 coexisted. This represents the triple point of methane (Shepherd et al. 1985). On heating (i.e. after stopping of freezing process) the fluid inclusions were homogenized (Th°C) at around, -85°C.

Primary biphase hydrocarbon rich fluid inclusions had pseudo-brownian motion at room temperature (~ 25 to 28°C) and gas bubble appeared to be yellowish brown. These fluid inclusions also showed low salinity and low temperature of homogenization, +100 to +150. The frequency of temperature of homogenization of these fluid inclusions and their salinity (primary monophase as well as primary biphase fluid inclusions) is given in Fig. 7a and b.

The secondary fluid inclusions of monophase nature showed similar characteristic as those of primary monophase hydrocarbon rich fluid inclusions, but indicated slightly higher temperatures of homogenization (Th°C).The temperature of homogenization of this type of fluid inclusions varied from,– 80 to -90°C.

The biphase secondary hydrocarbon rich fluid inclusions appear similar to the primary biphase fluid inclusions (CH_4 + CO_2) but have slightly higher temperature of homogenization, +130°C to +160°C. A few of these fluid inclusions were identified during heating and freezing studies as mixture of H_2O- NaCl-CO_2. The main features of this type of inclusions are the formation of 'clathrate'. On cooling of these fluid inclusions, the aqueous phase froze with the formation of tiny dark solid at around, -25°C to -35°C. This is referred to the first freezing/or initiating of freezing. On further cooling the dark bubble collapsed and the entire fluid inclusion was frozen at around, -50°C to -60°C, and no further change was observed. On heating (i.e. after stopping of freezing process) ice present in tiny fluid inclusion starts melting around, -30°C to -40°C, and the final ice crystal melting was recorded in the range of, -4°C to

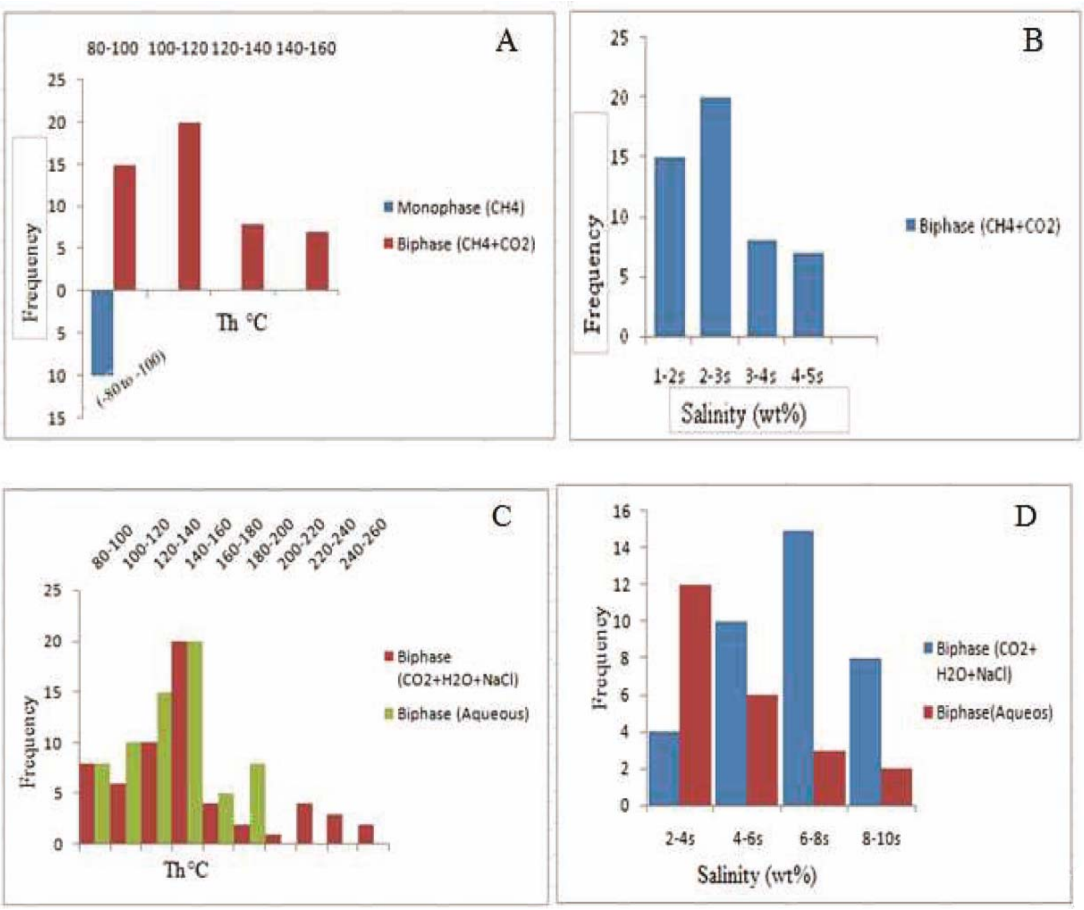

Fig.7. (**A**) Histograms of the temperatures of homogenization of primary monophase as well as biphase fluid inclusions, (**B**) Histograms showing the salinity (wt% of NaCl equivalent) of primary biphase fluid inclusions, (**C**) Histograms showing temperature of homogenization of secondary biphase fluid inclusion and (**D**) Showing their salinity (wt% of NaCl equivalent).

-5°C. The clathrate melting took place around, +8°C to +10°C. Homogenisation of this type of fluid inclusions was observed between, +140°C to +165°C. Histograms (Fig.7c and d) showed the distribution of the homogenization temperatures and salinity of the fluid inclusion hosted in the quartz grain of sandstone samples studies from the study area. A few of the fluid inclusions showed the formation of the solid CO_2 at around, -100°C to -120°C, and the final clathrate melting at about, +12°C to +16°C. This type of fluid inclusions showed a total homogenization around, +230°C to +250°C.

Some of the secondary fluid inclusions had aqueous phases only. These fluid inclusions showed two phases (L+V) at room temperature (~ 25°C to 28°C) with various degree of fill, characterized with wide ranges of sizes and shapes. A few of the secondary fluid inclusion showed necking and stretching phenomena. During freezing studies these fluid inclusions were completely frozen at a temperature range of, -40°C to-45°C. This change took place with a sudden shrinkage of the vapour bubble or deformation of the same, with the formation of ice within the fluid inclusion cavity appearing as a solidified crystalline mass. On controlled freezing up to a temperature range of, -25°C to -20°C, the ice was observed to be melting (granular appearance). The final ice melting was recorded at a temperature of, -8°C to -5°C. The final ice melting temperature, on the other hand, was used to determine the depression in freezing point or salinity (wt% of NaCl equivalent) of the fluid that trapped in particular fluid inclusions cavity. Complete homogenization in aqueous phase of the fluid inclusions took place around, +120°C to 180°C, but majority of the fluid inclusions homogenized between +120°C to +160°C.

FLUORESCENCE MICRO SPECTROSCOPY

Fluid inclusions are generally fluorescent if they contain cyclic or aromatic hydrocarbons or fluorescent daughter minerals (Burke, 2001). The relationship between fluorescence and chemical composition of petroleum are highly complex. The main fluorescing components in petroleum are aromatic hydrocarbons (Hagemann, 1986 and Khavari, 1987). Khavari (1987) showed fluorescence from the saturated fraction of petroleum with intensity maxima at low wavelengths in the blue–green range. The fluorescence of the saturated fraction was, however, most probably caused by contamination of minute quantities of aromatic hydrocarbons (Burke, 2001). In the present study several samples were analyzed, but the fluid inclusions which were nearer to the sample surface have shown the fluorescence effect. Generally most of them showed yellowish bright colour and a few of them were showing greenish yellow colour fluorescence. The bright yellow fluorescence of the primary fluid inclusions was typical of lower maturity oils with long chain n-alkanes and aromatics (Li and Parnell, 2003). The yellow-green fluorescence of the secondary fluid inclusions is, as a general rule, typical of higher maturity oils with more light n-alkanes and less aromatics (Li and Parnell, 2003; Feely and Parnell, 2003).

MICRO LASER RAMAN SPECTROMETRY

Micro Laser Raman Spectroscopy (MLRS) is commonly used to identify the chemical composition of fluid inclusions (Burke, 2001). Raman spectroscopy is extremely informative and useful for chemical identification, characterization of molecular structures and to study the effects of bonding, environment and stress on a sample. Guilhaumou (1982) has shown that Raman studies on hydrocarbon fluid inclusions are possible in spite of the obvious problems and difficulties. Most of the primary hydrocarbon bearing fluid inclusions were rich in normal paraffin, which have strong peak around 2870.48- 2936.35 cm^{-1} (Zhang , 2007). Methane rich fluid showed strong peak at 2917 cm^{-1} (Fig.8). Some of the secondary petroleum rich fluid inclusions have peaks around 2870-2970 cm^{-1} which relates to paraffin. Apart from paraffin, secondary petroleum rich fluid inclusions were also having some aromatic compound with peak at 3058 cm^{-1} (Zhang, 2007). Some of the secondary fluid inclusion was rich in CO_2 having peak at 1287 cm^{-1} (Fig.9).

RESULTS AND DISCUSSION

The primary fluid inclusions representing the early diagenetic phase of development of the Jaisalmer basin and are of two types, i) monophase gas and ii) liquid rich. Mostly CH_4 gas as well as liquid rich fluid inclusions were showing homogenization temperature between, -80°C to -100°C, with low salinity. The chemistry is further confirmed by Micro Laser Raman spectroscopy analysis. Biphase liquid rich fluid inclusions are mostly composed of CH_4- CO_2, H_2O- NaCl- CO_2. These were identified on the basis of phase changes during heating and freezing studies and is further supported by Micro-Laser Raman spectroscopy. The biphase fluid inclusions of CH_4- CO_2 having homogenization temperature from, +80°C to+150 °C, with inferred salinity variation between 3 to 6, wt% of NaCl equivalent. H_2O-NaCl- CO_2 biphase fluid inclusions, basically identified based on the clathrate formation (around +10°C) during freezing and heating studies, having final homogenization temperatures between, +100°C to +250 °C, in liquid phase with salinity variation from 6-10, wt% of NaCl equivalent. On the other hand biphase aqueous fluid inclusions have homogenization temperature from, +100°C to +180 °C, in liquid phase with inferred salinity variation in between 2 to 8, wt% of NaCl equivalent.

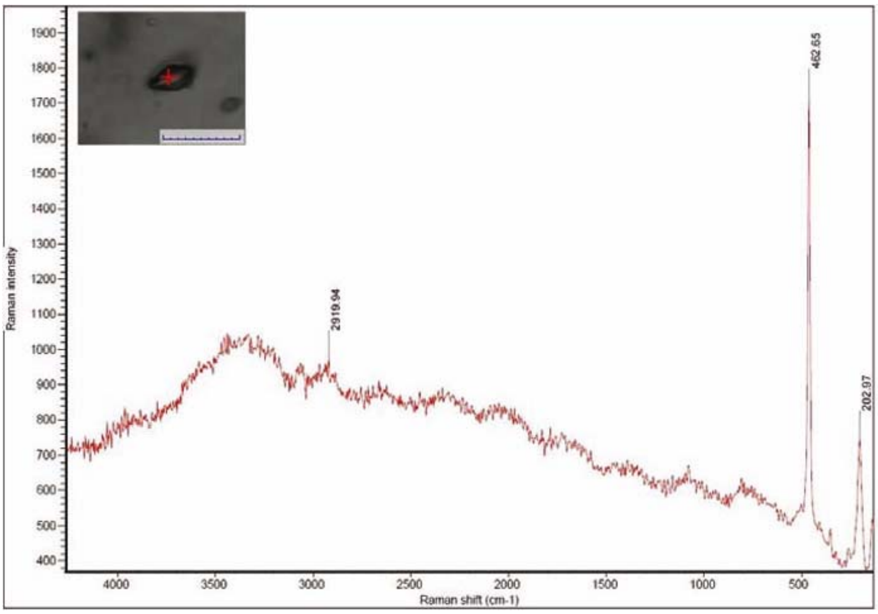

Fig.8. Micro Raman spectrogram of primary fluid inclusion in quartz grains of sandstone of Jaisalmer basin of Lower Goru formation showing peak of paraffin hydrocarbons. Inset shown photomicrograph of the inclusion analyzed. (Scale bar 10 μm).

The secondary fluid inclusions also had the presence of monophase

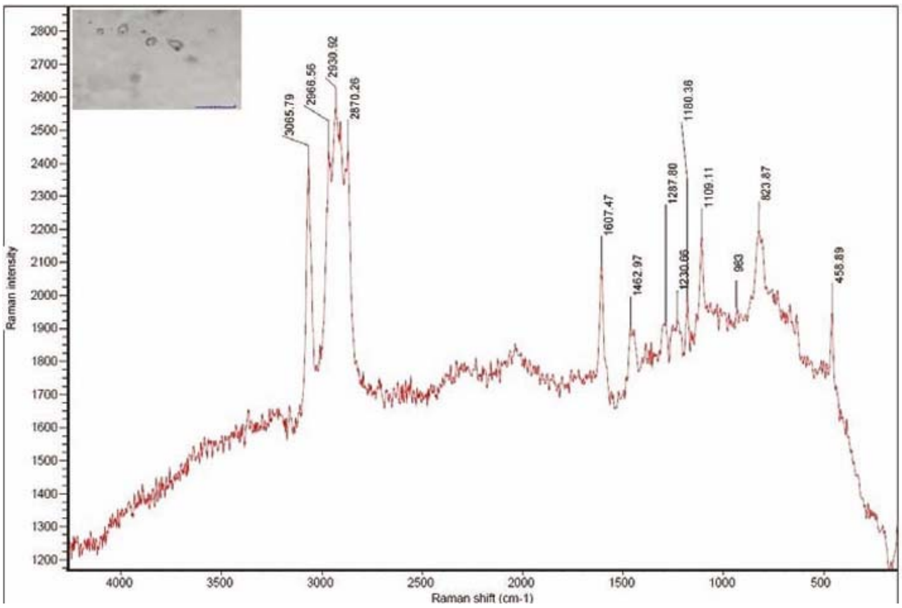

Fig.9. Micro Raman spectrogram of secondary fluid inclusion in quartz grains of sandstone of Jaisalmer basin of Lower Goru formation showing peaks of paraffin as well aromatic hydrocarbon and CO_2. Inset shown photomicrograph of the inclusion analyzed. (Scale bar 10 μm).

gas and liquid rich types. Both the types were having similar properties like monophase in primary types of fluid inclusions but with a slightly higher range of temperature of homogenization (-80°C to -90°C for monophase and +130°C to +160°C for biphase).

The Micro-Laser Raman examination revealed that the primary inclusion are mostly rich in paraffin (aliphatic) hydrocarbon while the secondary fluid inclusion were rich in both paraffin as well as aromatic hydrocarbons. Some of the secondary fluid inclusions have CO_2, as inferred from heating freezing studies. The fluorescence studies of a few of the selected fluid inclusions of primary petroleum rich types show greenish yellow colour, indicating aliphatic hydrocarbon, whereas the secondary petroleum rich fluid inclusions indicated the presence of aliphatic as well as aromatic hydrocarbons as they exhibited bright yellowish as well as greenish yellow colours in fluorescence studies. These kind of fluorescence colours, reflect the maturity of hydrocarbons (Li and Parnell, 2003). On the basis of this observation we could conclude that the primary petroleum rich fluid inclusions have experienced lower degree of maturity as compared to that of the secondary ones.

Regarding secondary petroleum rich fluid inclusions, there were three paleo-events of migration of hydrocarbon which were identified on the basis of cross-cutting relationship of different trails of fluid inclusions. There were also two events of cement generation identified on the basis of cross-cutting relation between fluid inclusion trails and host cement. So the first event of cement generation indicates the early stage of basin evolution and the second stage of cement generation i.e. after the entrapment of trails of fluid inclusions, and the third stage indicates the latest event of basin evolution/ micro tectonic effect on the host rocks of the study area.

CONCLUSIONS

The present study reported the presence of hydrocarbon rich fluid in the form of primary and secondary inclusion in the Jaisalmer basin. Primary fluid inclusions were best identified by their relationship to growth zonation of host quartz crystals. Growth zonations were identified through the variations in the distribution of fluid inclusion at the formation stage of host minerals. These fluid inclusion trails must have developed during lithification and diagenesis of the basin. Since aqueous fluids were dominating in sedimentary systems, the younger secondary aques-rich fluid inclusions were formed after complete crystal growth and generally got trapped along the micro-rehealed cracks in the respective quartz grains. Depending upon the paleo-temperatures and paleo-pressures, secondary fluid inclusions trapped in rehealed cracks were found with different liquid, gas/vapour ratios. The secondary fluid inclusions were more dominant as compared to the primary fluid inclusions. Micro-thermometry and fluorescence studies confirmed that the primary hydrocarbon fluid inclusions were of lower degree of maturity, whereas the secondary hydrocarbon fluid inclusions were having high degree of maturity. The fluorescence and Micro-Laser Raman data further indicated that the primary fluid inclusions were rich in aliphatic hydrocarbons, whereas, the secondary hydrocarbon fluid inclusions were rich in both aliphatic as well as aromatic hydrocarbons. The fluid inclusion petrographic analyses confirmed that there were three events of migration of hydrocarbons and at least two events of cement generation in the sandstone host rocks of the basin, indicating the relationship with early and late stage of basin evolution of the study area.

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